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Research & Development Report

Development of Low–Carbon, Copper–Strengthened HSLA Steel Plate for Naval Ship Construction

by

Ernest J. Czyryca

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Modern warships designs require an increased utilization of high strength, alloy steel plate for weight reduction, stability, increased payload, and increased mobility. Naval ship structures are subjected to a complex spectrum of loads and service environments, and the structural steels and welding materials used in hull fabrication must demonstrate high fracture toughness for these extreme service conditions.

The welding of the HY-series high strength steels, traditionally used in Navy ship construction, requires a number of fabrication controls to prevent weld cracking, which result in high fabrication costs. The Navy initiated the HSLA steel program with a goal of reducing shipbuilding costs. This report describes the development and certification of Cu-strengthened HSLA steels which are weldable with reduced parameter control (particularly preheat.), and provide high strength, high toughness, and high quality weldments.

HSLA-80 steel (MIL-S-24645) was certified for use in ship construction after an extensive program demonstrated that the low carbon, copper precipitation strengthened steel met the performance requirements of HY-80 steel, but was readily weldable without preheat. Lower fabrication costs and higher productivity in construction were realized. Following the HSLA-80 program, an alloy development and qualification program was conducted which resulted in HSLA-100 steel (MIL-S-24645A). HSLA-100 is also a low carbon, copper precipitation strengthened steel, meeting the strength and toughness of HY-100 steel, but weldable with lower preheat. HSLA-100 was also certified for use in ship construction over a wide range of plate gages.

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ABSTRACT

Modern warships designs require an increased utilization of high strength, alloy steel plate for weight reduction, stability, increased payload, and increased mobility. Naval ship structures are subjected to a complex spectrum of loads and service environments, and the structural steels and welding materials used in hull fabrication must demonstrate high fracture toughness for these extreme service conditions.

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HSLA–80 steel (MIL–S–24645) was certified for use in ship construction after an extensive program demonstrated that the low carbon, copper precipitation strengthened steel met the performance requirements of HY–80 steel, but was readily weldable without preheat. Lower fabrication costs and higher productivity in construction were realized. Following the HSLA–80 program, an alloy development and qualification program was conducted which resulted in HSLA–100 steel (MIL–S–24645A). HSLA–100 is also a low carbon, copper precipitation strengthened steel, meeting the strength and toughness of HY–100 steel, but weldable with lower preheat. HSLA–100 was also certified for use in ship construction over a wide range of plate gages.

ADMINISTRATIVE INFORMATION

This report presents an overview on the development and certification of HSLA–80 and HSLA–100 steel plate for naval construction. The studies of modified HSLA–80/100 steel was conducted under the Submarine Materials (Structural) Block Program under Program Element 62234N. The Block Program is managed by Mr. I. L. Caplan, David Taylor Research Center (DTRC 0115).

The studies of HSLA–100 steel were conducted as part of the program to certify HSLA–100 steel for submarine non-pressure hull structures. The program was sponsored in part by the SEAWOLF Acquisition Program of the Naval Sea Systems Command (NAVSEA PMS 350AT) under Program Element 64561N. The program was partially supported by the Aircraft Carrier Program (NAVSEA PMS 312), under Program Element 64567N. The NAVSEA Technical Agent for both programs was Mr. C. L. Null (NAVSEA 05M2).

The work was conducted under the supervision of Mr. T. W. Montemarano, Head, Fatigue and Fracture Branch (DTRC 2814).

INTRODUCTION

Nearly 50% of the total Department of Defense requirement for carbon, alloy, and armor steel plate is used in shipbuilding. Modern warship design in the past two decades continued a trend of increased utilization of high strength, alloy steel plate for weight reduction, increased payload, and increased mobility. Naval ship structures are subjected to a complex spectrum of dynamic loadings and stresses built into the hull during

fabrication and fit-up. The routine dynamic loads in service include wave loadings, sea slap, slamming, vibration, thermal excursions, cargo bouyancy, aircraft/helo landing, and weapons reactions [Palermo, 1975]. The ship structure must operate in both tropical and arctic seas over a temperature range of -30° to +120°F.

The structural integrity of the hull must be assured in these severe environments, as well as in response to the effects of hostile weapons. The dynamic loadings, particularly in the form of shock waves, must be considered when assessing materials performance and fracture safety [Palermo, 1976a]. The fracture safety of Navy ships is addressed through the use of structural steels and welding materials used in hull fabrication must demonstrate high fracture toughness and flaw tolerance for these extreme service conditions [Palermo, 1976b].

The high strength steels traditionaly used in Navy ship construction, HY–80 and HY–100, were certified to meet these requirements [Heller et al, 1965a, 1965b]. However, the welding of the HY–series steels requires a number of fabrication controls to prevent post-weld cracking, which result in high fabrication costs. These include preheat requirements; interpass temperature limits; controls on electrode preparation, storage, and issue; heat input limits; weld sequencing requirements; weather protection; constraint reduction; welder training and qualification; and intensive inspection procedures.

The Navy initiated the HSLA steels research and development program with a goal of reducing shipbuilding costs. The technical objective was the development and certification of high strength steels and welding consumables, which are weldable with lessened parameter controls (particularly preheat), to provide high strength, high toughness, and high quality weldments equivalent in performance to the HY–series steels.

In the early 1980's, the major steelmakers were producing large tonnages of HSLA steel plate of improved weldability and low temperature toughness with yield strengths of 60 to 80,000 psi (415 to 550 MPa). An evaluation confirmed the feasibility of developing one of several types of HSLA steels to meet the mechanical properties and fracture toughness of HY–80 steel, but weldable without preheat.

HSLA–80 STEEL DEVELOPMENT AND CERTIFICATION

The HSLA steel development program identified and evaluated ASTM A710, Grade A steel as the prime candidate among a number of candidate commercial HSLA steel plate products which met a minimum yield strength requirement of 80 ksi yield strength through 3/4 inch gage, had high Charpy V-notch impact energy at low temperatures, and demonstrated excellent weldability [Montemarano et al, 1986]. A710 steel was selected since it was in commercial production, and short-term modification could result in an easily weldable replacement for HY–80. Other steels considered included low-carbon, controlled-rolled and quenched and tempered HSLA line-pipe steels, which typically could not meet the minimum Charpy V-notch impact toughness requirement of 35 ft-lb at -120°F.

In 1984, HSLA–80 steel (MIL–S–24645) was certified for use in ship construction. Certification requires an evaluation of a structural fabrication system which demonstrates that the system will perform in all aspects of structural performance equivalent to or better than the system it replaces. Material specifications and fabrication/inspection documents are based on the results of the certification program. An extensive evaluation

of HSLA–80 properties, welding, and structural performance [Montemarano et al, 1986] demonstrated that the low carbon, copper precipitation strengthened steel met the requirements of HY–80 steel, and was readily weldable with no preheat (32°F maximum) using the same welding consumables and processes as for HY–80 steel fabrication.

A substantial reduction in hull fabrication costs and higher productivity was achieved through substitution of HSLA–80 for HY– 80 due to the reduced process controls and NDT requirements. The significant factor in cost savings through use of HSLA–80 steel in fabrication is the reduction or elimination of preheat for welding [Kvidahl, 1985]. HSLA–80 steel is a primary structural steel used in construction of the *Ticonderoga* class cruisers, the new *Arleigh Burke* Class destroyers, in some structure of the later *Nimitz* Class aircraft carriers, and *Wasp* Class amphibious assault ships. Over 20,000 plate-tons of HSLA–80 steel to MIL–S–24645 have been delivered for use in ship construction. Production has primarily been in plate gages up through 3/4 inch.

HSLA–100 STEEL DEVELOPMENT

Following the successful HSLA–80 program, an alloy development and qualification program commenced in 1985, which resulted in HSLA–100 steel as a replacement for HY–100 in order to reduce fabrication costs. HSLA–100 is also a low carbon, copper precipitation strengthened steel, based on different metallurgical principles than HSLA–80, meeting the strength and toughness of HY–100 steel, but weldable without the preheat requirements of HY–100, using the same welding consumables and processes as used in welding of HY–100. HSLA–100 (MIL–S–24645A) was certified in 1989 for use in surface ship structures as a replacement for HY–100 over a wide range of plate gages.

The composition ranges of HSLA–100 steel were formulated from a progressive optimization of the alloy design by laboratory scale heats. The resulting composition was formulated to achieve the required strength, toughness, and weldability in heavy plate product (30 to 50 mm). HSLA–100 laboratory plates in thicknesses of 6, 19, 32, and 50 mm exceeded the minimum strength, impact toughness, and welding requirements. The results of the laboratory phase were used to develop an "Interim Specification for HSLA–100 Steel Plate" to be used for trial commercial production of HSLA–100 steel plate. The composition range for HSLA–100 steel, as given in the military specification, is shown in Table 1, compared with the specified composition ranges for HY–80, HY–100, and HSLA–80.

METALLURGY OF HSLA–80 AND HSLA–100 STEELS

HSLA–80, an optimized version of ASTM A710, Grade A steel, is a ferritic steel. The microstructure of the quenched and aged plate product is generally an acicular ferrite in gages less than about 1/2 inch, but polygonal ferrite in thicker plate [Wilson, 1987; Jesseman and Murphy, 1984]. Ferritic steels typically demonstrate a impact toughness transition curve with a steep drop in toughness over a narrow temperature range. Results of studies of the fracture process of HSLA–80 steel [Gudas, 1985; Speich and Scoonover, 1988; Natishan, 1989; Gudas et al, 1989] showed that the coarse-grained polygonal ferrite, with islands of carbide-containing secondary transformation products, were deleterious to low-temperature cleavage fracture resistance.

Table 1. Chemical compositions of high strength structural steels. (Major elements for heavy gage plate, greater than 1 inch)

Element (weight %)	Specified Chemical Composition (maximum unless a range is shown)			
	HY–80 MIL–S–16216K	HSLA–80 MIL–24645A	HY–100 MIL–S–16216K	HSLA–100 MIL–S–24645A
C	0.13–0.18	0.06	0.14–0.20	0.06
Mn	0.10–0.40	0.40–0.70	0.10–0.40	0.75–1.05
P	0.015	0.020	0.015	0.020
S	0.008	0.006	0.008	0.006
Si	0.15–0.38	0.40	0.15–0.38	0.40
Ni	2.50–3.50	0.70–1.00	2.75–3.50	3.35–3.65
Cr	1.40–1.80	0.60–0.90	1.40–1.80	0.45–0.75
Mo	0.35–0.60	0.15–0.25	0.35–0.60	0.55–0.65
Cu	0.25	1.00–1.30	0.25	1.45–1.75
Cb	nil	0.02–0.06	nil	0.02–0.06

The design of HSLA–100 resulted in an optimized chemistry and heat treatment which produced plate product with a bainitic microstructure in all gages. Transmission electron microscopy studies have shown evidence of a low-carbon martensite microstructure in lighter gage plates [Wilson et al, 1988]. In heavy plate (2 inch thick and greater), however, granular bainite structures were typically identified [Wilson et al, 1988]. The HSLA–100 alloy design produced a homogeneous microstructure which dispersed the secondary transformation products. Such a microstructure was considered desirable for ensuring upper-shelf toughness for all plate gages at low temperatures. In HSLA–100, the nickel content was significantly increased to lower the impact toughness transition temperature in heavy plate product.

Figure 1 compares photomicrographs of both HSLA–80 and HSLA–100 plates in light and heavy gage. Prior austenite grain sizes in both steels ranged from ASTM No. 12 in thinner plate to ASTM No. 9 in thick plates.

HSLA–100 STEEL CERTIFICATION

The Interim Specification was used as the basis for several commercial full-production melts of HSLA–100 steel. Over 250 plate-tons of HSLA–100 steel have been rolled and heat treated as a result of several production melts. Plate gages ranged from 1/4 to 3–3/4 inches. HSLA–100 steel production has been by conventional electric furnace practice and ingot casting. Melting and refining practices typically included extended decarburization to achieve a very low carbon, extra-low sulfur practice, vacuum degassing, ,and calcium treatment for inclusion shape control, employing argon stirring or blowing. Double austenitization and quench was used for HSLA–100 steel plate in gages over 1–1/4 inches, to refine grain structure for optimum toughness [Hamburg et al, 1987; Wilson et al, 1988].

PHYSICAL PROPERTIES

The physical properties measured for HSLA–100 steel included density, thermal conductivity, and coefficient of thermal expansion. The density of HSLA–100 was 0.284 lb/in^3 (7.862 g/cc), as compared to 0.283 lb/in^3 (7.834 g/cc) for HSLA–80 steel and 0.28 lb/in^3 reported for HY–80 and HY–100 steels [Alloy Digest, 1966 and 1970]. Experimental determination of thermal properties used standard heat flow and dilatometry methods. Thermal conductivity and values for mean coefficient of thermal expansion of HSLA–100 is compared to HY steels in Table 2. The dilatometry data indicate that for HSLA–100 steel the A_{c1}, lower transformation temperature, was approximately 1250°F, and the A_{c3}, upper transformation temperature, was approximately 1500°F. Corresponding values for HY–80 steel are A_{c1} = 1320°F, A_{c3} = 1470°F.

Table 2. Comparison of thermal conductivity and mean coefficient of thermal expansion of high strength steels.

Temperature		Thermal Conductivity (W/m-c)		
°C	°F	HSLA–100	HY–80	HY–130
21	70	35.6	32.8	27.7
427	800	36.3	34.5	32.8
538	1000	35.1	32.8	32.2

Temperature Range °F	Mean Coefficient of Thermal Expansion (ppm/°F)			
	HSLA–100	HY–80	HY–100	HY–130
80 to 1000	6.91	7.0	7.7	7.3

MECHANICAL PROPERTIES

The modulus of elasticity and Poissons's ratio of HSLA–100 steel, were measured by precision methods. The results from multiple test runs are E = 28.582 ± 0.253 Mpsi and ν = 0.2916 ± 0.0337. Values of E from 28 to 30 Mpsi have been used for HY–80 and HY–100 steels [Alloy Digest, 1966 and 1970]. The shear modulus (modulus of rigidity), G, was measured for HSLA–100, using a torsional test of a bar sample, and ranged from 11.5 to 11.9, with an average value of 11.7 Mpsi.

HSLA–100 plates in gages from 1/4 to 3–3/4 inches achieved the required tensile properties:

- Minimum 0.2% offset yield strength = 100,000 psi;
- Maximum 0.2% offset yield strength = 120,000 psi;
- Minimum elongation in 2 inches = 18%;
- Minimum reduction in area = 45%.

However, lighter gage plates were in some cases aged as high as 1275° F, exceeding the A_{c1}, lower transformation temperature, of about 1250°F, in order to keep below maximum yield strength limits. The HSLA–100 alloy was formulated to meet strength and toughness in 2–inch–thick plate, with the consequence that thin gage plates required high aging temperatures and longer aging times to achieve a yield strength within the specified range. Tensile strengths ranged from 116 to 129 ksi, elongation from 18 to 33%, and reduction of area from 53 to 78%; where the low values were measured on the 3–3/4 inch plate.

The compressive 0.2% yield strength (CYS) was slightly higher than the tensile yield strength (TYS). The ratio of TYS to CYS of HSLA–100 was approximately 0.95, similar to HY–80 and HY–100 steels. Shear properties of HSLA–100 steel plate were measured by torsion tests to determine the yield and ultimate strength in shear and the shear ductility. The average yield stress in shear was approximately equal to the theoretical value of $(1/\sqrt{3})$ times the yield strength in tension, and the ultimate shear strength was within the typical range of 2/3 to 3/4 of the tensile strength [Brokenbrough and Johnston, 1968].

Charpy V-notch (CVN) impact tests were conducted for each plate to develop toughness transition curves. CVN transition curves for the T-L orientation of 1–inch–thick plates are presented in Fig. 2. The CVN impact requirements of 60 ft-lb at 0°F and 40 ft-lb at –120°F of MIL–S–16216K for HY–100 steel, were easily exceeded. HSLA–100 plates exhibited upper shelf impact performance (100% shear fracture) to temperatures below –60°F for all plate gages. The 50% fracture area transition temperature (FATT) was below –120°F for all plate gages.

Dynamic tear tests (ASTM E604) were conducted using 5/8–inch–thick specimens for HSLA–100 plates. The complete DT transition curves for T-L orientation of the same 1–inch–thick plates are presented in Fig. 3. All of the HSLA–100 plates tested, with the exception of an early 2–inch gage plate, exceeded the minimum energy of 500 ft-lb at –40°F specified by MIL–S–16216K for HY–100 steel. Erratic toughness in early heavy plate was due to a lack of experience with HSLA–100 plate processing. Slabbing and hot rolling schedules, as well as heat treating and quenching parameters, exert a significant influence on the strength and toughness of high strength steel plate [Lankford et al, 1985]. Later production HSLA–100 plates in gages from 2 to 3–3/4 inches showed high DT energies.

The nil-ductility temperature was determined using the ASTM E208 drop-weight test method. Type P-2 specimens were prepared from 3/4–inch–thick HSLA–100 plate. The test samples were oriented such that the notch in the crack starter weld was transverse to the plate rolling direction. The NDT for HSLA–100 was determined to be –210°F.

Elastic-plastic fracture toughness was measured throughout the entire ductile-brittle transition region using the J-integral method. Fatigue precracked, side-grooved compact tension-type specimens and the computer-interactive, unloading compliance method [Joyce and Gudas, 1979] were used to estimate energy and crack extension at regular intervals during each test. Room temperature J-resistance curves for HY–100 and HSLA–100 are compared in Fig. 4. J_{Ic} measured at room temperature for 2–inch–thick

HSLA–100 and HY–100 plate was 2130 and 850 in-lb/in^2, respectively. In general, the fracture toughness of HSLA–100 steel was from 2 to 2.5 times that of HY–100.

WELDING AND WELDABILITY

The objective of the welding evaluation was to demonstrate that welding of HSLA–100 steel, using the HY–100 steel welding products, with minimal restrictions on preheat and interpass temperatures, met strength and toughness requirements with no weldment cracking. For each of three major welding processes, shielded metal-arc (SMAW), submerged arc (SAW), and gas metal-arc (GMAW), the limits on welding heat input, preheat temperature, interpass temperature, and plate thickness for obtaining the required weld metal strength and toughness were determined.

Variations in welding process parameters change weld metal cooling rates, which control weld metal strength and toughness. A large range of cooling rate conditions, in the range of 10 to 100°F per second, were developed in experimental GMAW, SMAW, and SAW joints. All-weld metal tensile tests, weld metal and heat affected zone impact toughness tests, weld metal chemical analysis, and weldment hardness profiles were used to assess each joint. The results showed that the required strength and toughness could be achieved in HSLA–100 weldments fabricated with HY–100 type welding consumables. The strength and toughness deficiencies observed in some of the HSLA–100 weldments were due to inherent limitations of the welding consumables employed, i. e. low yield strength welded at very low cooling rate and low toughness at either very low or very high cooling rates.

Hardness measurements across the base plate, HAZ, and weld metal on each welding process gave profiles like that shown in Fig. 5 for the GMAW–P weldments. Unlike quenched and tempered, martensitic HY–100 steel, HSLA–100 did not exhibit a pronounced hardness increase in the heat affected zone of any weldment. No "hard" microstructures were indicated and Charpy V-notch toughness of the HSLA–100 weldment heat affected zones were equal to or greater than the weld metal toughness. Also, chemical analysis of weld metal deposits showed that some copper had been diluted into the weld metal deposit, but carbon content was less than the wire electrode.

The primary reason for welding preheat is to mitigate underbead cracking (hydrogen related) in the hard, martensitic heat-affected zone (HAZ) of the HY steels. The HAZ of HSLA–80 steel typically does not harden from the heat of welding, but may soften due to the dissolution of copper and grain coarsening [Jesseman and Schmid, 1983]. Both the low-carbon HSLA–80 and HSLA–100 steel HAZ microstructures are less sensitive to hydrogen damage to achieve excellent weldability. The HAZ in HSLA–100 weldments, however, was not prone to soften in the HAZ, due to the increased hardenability available.

A variety of high-restraint weldability tests were conducted to determine the lowest practical preheat and interpass temperatures needed to prevent cracking (weld metal or HAZ) in the welding of HSLA–100. These focus on the sensitivity of weldments (weld metal and HAZ) to hydrogen cracking (cold cracking) and to hot cracking. The weldability testing conducted on HSLA–100 included: (1) implant testing, (2) controlled thermal severity (CTS) tests, (3) restrained butt weld-root pass specimens, (4) trough tests, (5) explosion bulge tests, and (6) cruciform tests, as described in Fig. 6.

Implant tests are specifically designed to focus on HAZ cracking resistance. Initial results from implant testing indicated higher stress levels (100–130 ksi) were required to initiate heat affected zone hydrogen cracking in HSLA–100 compared to HY–100 (70 ksi). Cracking initiated and grew only in the weld metal deposit and not the HAZ. The evaluation of hydrogen cracking resistance in the root pass of a restrained butt weld and cruciform tests with a 60°F preheat/interpass temperature showed different levels of cracking resistance for the different welding process and consumable combinations. All cracks observed were confined to the weld metal.

The CTS evaluation of HAZ/underbead cracking characteristics of HSLA–100 steel showed small weld metal cracks using SMAW and SAW processes without preheat, and no cracking for GMAW. In no case were HSLA–100 HAZ cracks evident. As a control, an HY–100 specimen welded without preheat (SMAW) exhibited both weld metal and HAZ cracks. No indications of hydrogen-damage were observed in the magnetic particle testing (MT), macro and microscopic cross-section examination, and tensile tests of HSLA–100 trough test all-weld metal specimens. However, reduced ductility associated with hydrogen embrittlement was observed in the HY–100 tensile specimens removed from trough tests fabricated without preheat.

The hot cracking resistance of welds deposited in HSLA–100 was evaluated by varestraint tests. The results, illustrated in Fig. 7, indicate the hot cracking resistance of HSLA–100 is similar to that observed in HSLA–80 and better than HY–80.

In summary, the weldability testing indicated that the HAZ of HSLA–100 steel was significantly more resistant to hydrogen cracking than HY–100, such as to allow a relaxation of preheat requirements. However, the weld metals were the "weak link" in the weldability of the 100 ksi yield strength base plate/weld metal system. Weld metals deposited by the flux-assisted welding processes (SMAW and SAW) were less resistant to hydrogen cracking than the GMAW process.

Based on the welding and weldability evaluations of HSLA–100, welding preheat/interpass temperature limits were formulated. For general construction, i.e. nominal restraint conditions, it was concluded that welding with the GMAW process (MIL–120S–1 wire) or the SMAW process (E12018 electrode) will produce acceptable weldments when using 60°F minimum preheat and interpass temperatures of 60°F minimum and 300°F maximum. Under highly restrained conditions (tack welds, thick-section corner joints, etc.), higher preheat temperatures may be necessary to prevent SMAW weld metal cracking. The preheat/interpass requirements for the SAW process must be the same as HY–100 welding to prevent weld metal cracking.

The longitudinal and transverse shear strength of HSLA–100 GMAW and SMAW weldments in two fillet sizes, using HY–100 filler metals, were measured using standard shear strength tests (ANSI/AWS B4.0. 1985). The fillet weld strengths were equivalent to HY–100 welds using the same process, filler metal, and fillet size.

Other findings of the HSLA–100 certification evaluation were as follows:

- It was demonstrated that HSLA–100 fillet weld strengths were equivalent to HY–100 welds using the same process, filler metal, and fillet size.

- Explosion bulge and crack starter explosion bulge tests of 2–inch gage HSLA–100 GMAW, SMAW, and SAW weldments, fabricated within the

recommended preheat/interpass temperatures and passed the requirements for HY–100 weldments given by MIL–S–16216K.

- The results of the low-cycle fatigue crack initiation studies of HSLA–100 steel and weldments under cyclic loading in air and in marine environments showed equivalent low-cycle fatigue performance to HY–100 steel and weldments in every case.

- Both HSLA–100 and HY–100 steels showed similar high-cycle fatigue properties. High-cycle tests of HSLA–100, HY–100, and HY–80 GMAW butt weldments demonstrated that all the weldments had similar fatigue properties. HSLA–100 and HY–100 exhibited similar fatigue crack growth rates.

- General corrosion, crevice corrosion, galvanic corrosion, high velocity seawater parallel flow and cavitation tests of HSLA–100 steel in seawater showed that the corrosion behavior of HSLA– 80, HY–80, and HSLA–100 steels were comparable.

- HSLA–100 plate, HAZ and weld metal exposures have not shown any susceptibility to stress corrosion cracking when exposed at –1000 mV at or above stress corrosion cracking threshold stress intensity values determined for HY–100 and 120S weld metals.

The properties and weldability demonstrated by HSLA–100 steel resulted in certification of HSLA–100 (MIL–S–24645A) as a replacement for HY–100 for ship construction in 1989. The Navy has research in progress to develop welding consumables specificallyfor HSLA–100 in order to achieve preheat-free welding by all processes. However, the lesson learned from the HSLA–100 program regarding the development of steel systems of greater strength was that initial focus must be on weld metal and welding product development. Plate development will be the less difficult endeavor.

The nominal compositions of HY–80, HY–100, HSLA–80, and HSLA–100 are compared in Fig. 8, showing the calculated carbon equivalents for the steels [Rothwell, 1977]. HSLA–80 and HSLA–100 demonstrated that very low carbon content leads to good weldability, even with significant alloying and high carbon equivalent.

EXPANSION OF THE Cu-STRENGTHENED STEEL SYSTEM

As previously discussed, HSLA–80 has been used in ship construction in plate gages up through 3/4 inch, utilization was not extended to heavy plate applications due to inconsistent fracture toughness in the heavier gages. The studies of the fracture process in HSLA–80 steel [Gudas, 1985; Natishan, 1989; Gudas et al, 1989] showed that coarse-grained polygonal ferrite, and accumulation of secondary transformation products were deleterious to low-temperature cleavage fracture resistance. The brittle fracture process model for heavy plate HSLA–80 was postulated from these studies to be as follows: (1) cleavage crack initiation in the carbide-rich islands followed by (2) crack propagation across ferrite grains to a distance sufficient for the crack front to gain energy sufficient for self- propagation (unstable fracture).

The results indicated that a uniformly small grain size and wider distribution of small carbides would reduce the fracture transition temperature. The key to the HSLA–100 alloy design was requirement to produce a homogeneous microstructure which dispersed the secondary transformation products. Thus a bainitic microstructure was deemed most desirable from the standpoint of ensuring upper shelf performance for all plate gages at all service temperatures.

An alloy development effort was conducted to microstructurally modify HSLA–80 steel to obtain greater low temperature toughness in heavy sections. Laboratory-scale heats were used to study the effects of Mn, Ni, Mo, Cu, Cr, Cb and C in hot rolled, quenched and aged HSLA–80 plate. Microstructural analysis was conducted to develop composition ranges, meeting the strength and toughness requirements, where ferritic microstructures were not present. A regression analysis was conducted on the results for plates from 45 experimental melts to develop low carbon, copper precipitation strengthened HSLA–80 steel composition ranges for an interim specification for plate production.

In the production of HSLA–100 steel plate to the Interim Specification, difficulties were experienced in keeping below the maximum yield strength requirement of 115,000 psi in plate 1–1/4–inch thick and less, unless very high aging/tempering temperatures were used. These results suggested that a much leaner composition could meet HSLA–100 requirements in thinner plate gages. Thus, the development program for modification of HSLA–80 included analysis to formulate a recommended chemistry range for both a lower cost HSLA–100 plate product for gages less than 1 inch, and heavy plate HSLA–80 with improved low temperature toughness. Composition ranges for an "Interim Specification for HSLA–80/100 Steel Plate" were formulated, as given in Table 3.

The overlapping chemistry ranges of the Interim Specification allowed for the production of a 165–ton electric furnace melt of modified HSLA–80/100 steel, for lower cost HSLA–100 plate in gages less than 1 inch and heavy plate HSLA–80 with improved low temperature toughness. Strength and impact toughness data for plates rolled and heat treated to meet the requirements for HSLA–100, with the leaner modified composition, and plates to meet HY–80 requirements in heavy plate HSLA–80 are shown in Table 4.

An evaluation program is in progress to support the certification of modified HSLA–80 and intermediate composition HSLA–100 steel plate compositions, shown in Table 3, for use in ship construction. The program includes tasks on the characterization of mechanical properties of production plate, weldability and welding process limits for structures of increased restraint, explosion bulge testing, studies of fatigue behavior, and evaluation of stress corrosion in marine environments.

Table 3. Chemical compositions ranges for proposed HSLA–80/100 steel plate specification.

Element (weight %)	Specified Chemical Composition (maximum unless a range is shown)			
	Grade HSLA–80		Grade HSLA–100	
	Plate Gage (inches)			
	3/4 and less	> 3/4	1 and less	>1
C	0.06	0.06	0.06	0.06
Mn	0.40–0.70	0.85–1.15	0.75–1.15	0.75–1.05
P	0.015	0.015	0.015	0.015
S	0.006	0.005	0.006	0.005
Si	0.40	0.40	0.40	0.40
Ni	0.70–1.00	1.70–2.00	1.50–2.00	3.35–3.65
Cr	0.60–0.90	0.45–0.75	0.45–0.75	0.45–0.75
Mo	0.15–0.25	0.45–0.55	0.30–0.55	0.55–0.65
Cu	1.00–1.30	1.00–1.30	1.00–1.30	1.45–1.75
Cb	0.02–0.06	0.02–0.04	0.02–0.04	0.02–0.06

Cu-STRENGTHENED STEELS BEYOND HSLA–100

Opportunities for achieving reductions of welding preheat requirements, higher welding productivity, and reductions in inspection requirements in hull steel systems with yield strengths beyond HSLA–100 is dependent on research to develop welding processes and welding consumables to allow preheat-free welding with high strength and toughness in cracking-resistant weld metals.

The Navy has a continuing HSLA steels research and development program. The emphasis continues in both the development of lower-cost alternatives to the HY steel systems and the development of high strength welding products and welding processes for higher productivity. The goal is to achieve reductions in the overall total of plate, fabrication and inspection cost. The HSLA steel plate development program includes extension of the metallurgical approach used in HSLA–80/100 of replacing carbon strengthening with very low carbon, Cu-strengthed steels, the development of thermo-mechanically processed ULCB (ultra-low carbon bainitic), and direct-quenched (DQ) alloy steels to meet Navy performance goals. The research effort is exploring the feasability of pushing these goals to achieving a 65 to 150 ksi yield strength steels ammenable to high technology welding processes.

Table 4. Mechanical properties for Grade HSLA–80 and HSLA–100 production plates (modified composition).

Ladle Chemistry										
C	Mn	P	S	Si	Ni	Cr	Mo	Cu	Al	Cb
0.05	1.00	.009	.001	.34	1.77	.61	.51	1.23	.025	.037

Plate Gage (in)	Yield Strength (ksi)	Tensile Strength (ksi)	Elongation (%)	Reduction of Area (%)	Charpy V-notch Impact Energy (ft–lb)	
					0°F	–120°F
Grade HSLA–80						
3/4	87.0	106.9	22	74	207	200
1	92.5	107.7	34	66	180	159
1–1/4	95.1	103.5	26	77	209	180
2	93.6	103.5	21	74	199	120
2–1/2	84.4	97.9	28	76	220	161
Grade HSLA–100						
3/16	113.2	114.3	23	–	–	–
1/4	102.7	105.1	23	67	76*	69*
3/8	110.6	113.6	28	–	–	–
1/2	111.2	114.1	29	–	187	144
9/16	107.8	110.7	30	65	183	154
1	110.7	117.4	20	68	165	125
1–1/4	109.3	117.0	22	73	194	134
2	107.2	119.8	21	70	138	90

* = Subsize specimens.
Note: All properties are averages for transverse (T–L) orientation.

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Thanks are also given to Dr. R. J. Fields and Mr. G. E. Hicho of the Fracture and Deformation Division of the National Institute of Standards and Technology, Gaithersburg, MD for the precision work conducted to determine physical properties described in this paper.

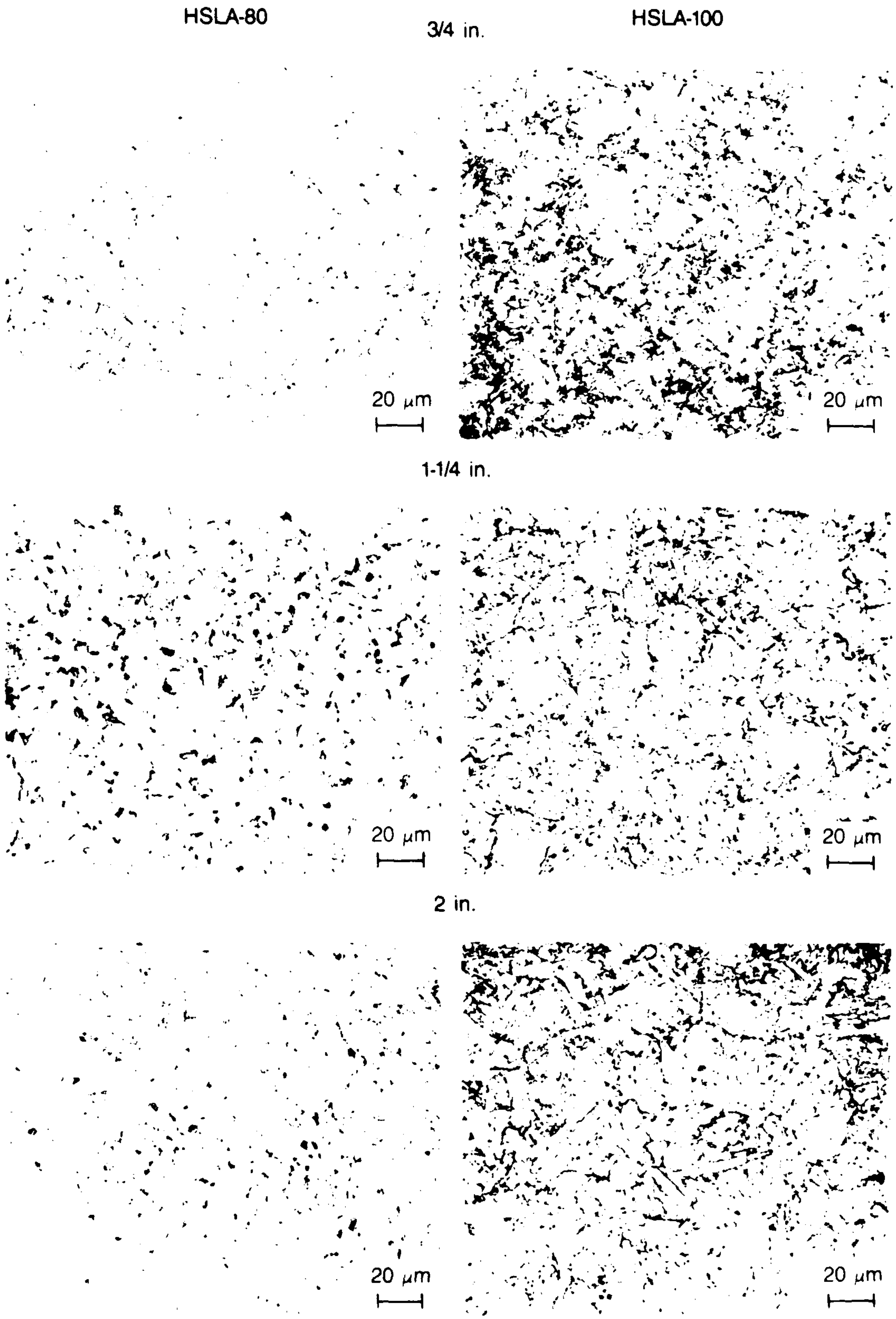


Fig. 1. Photomicrographs of HSLA–80 and HSLA–100 steel plate microstructures, 2% nital etch.

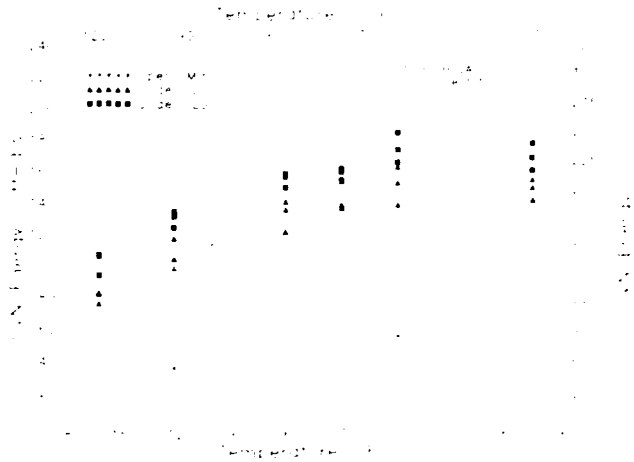


Fig. 2. Charpy V-notch impact energy transition for typical HSLA–100 steel plate, I–in. thick.

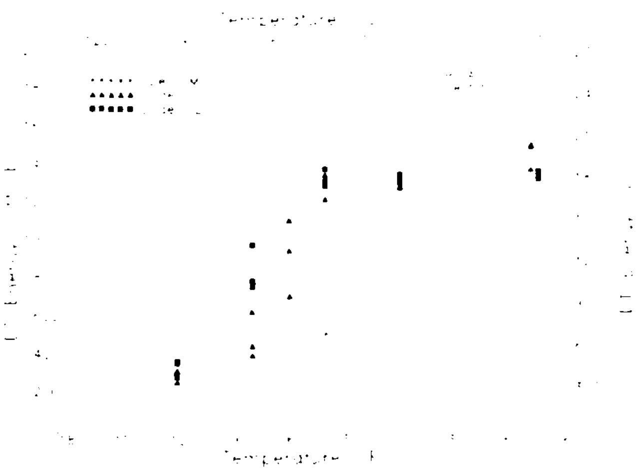


Fig. 3. Dynamic tear energy transition for typical HSLA–100 steel plates, I–in. thick.

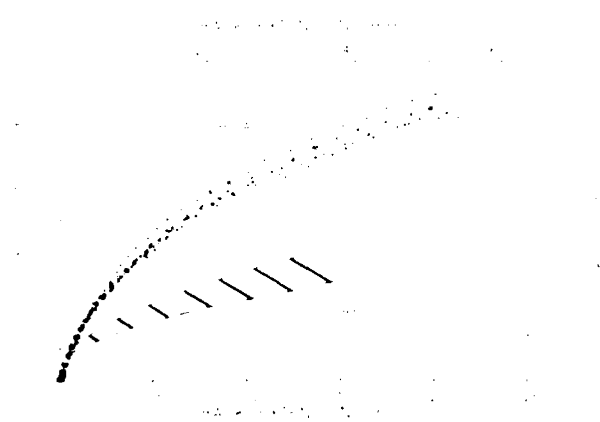


Fig. 4. Comparison of J-resistance curves for HSLA–100 and HY–100 steel at room temperature.

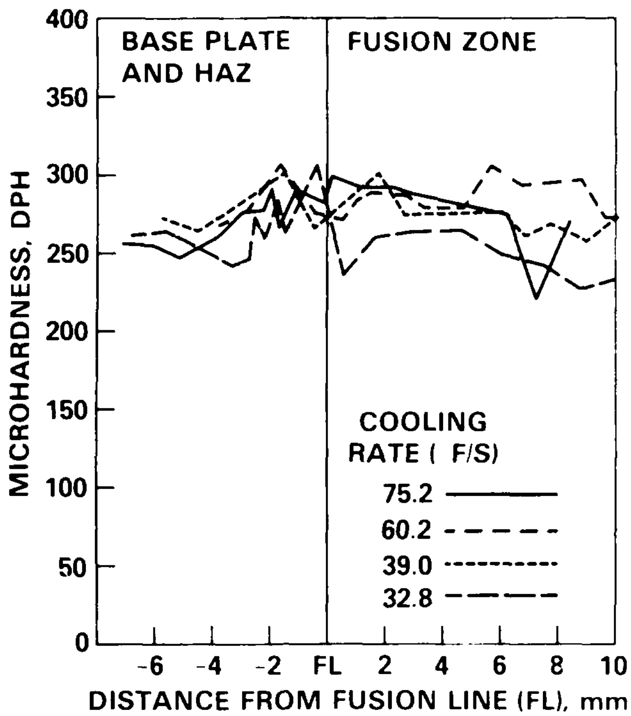


Fig. 5. Microhardness profiles of HSLA–100 GMAW joint cross-sections.

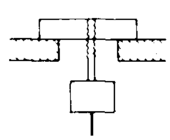
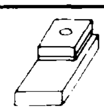
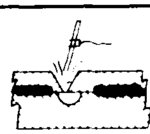
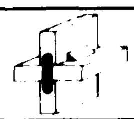
	IMPLANT TEST	DETERMINES CRITICAL STRESS FOR HAZ HYDROGEN CRACKING
	CONTROLLED THERMAL SEVERITY	EVALUATES HAZ UNDERBEAD CRACKING CHARACTERISTICS
	RESTRAINED ROOT CRACKING	EVALUATES ROOT AND HAZ COLD CRACKING
	TROUGH WELDMENT	SIMULATES HIGH RESTRAINT OF TYPICAL WELD REPAIR
	EXPLOSION BULGE	EVALUATES PROCESS STABILITY INCLUDING DYNAMIC LOADING CHARACTERISTICS OF ENTIRE WELDMENT
	CRUCIFORM TEST	DETERMINES UNDERBEAD CRACKING CHARACTERISTICS

Fig. 6. Weldability tests used in HSLA–100 evaluation.

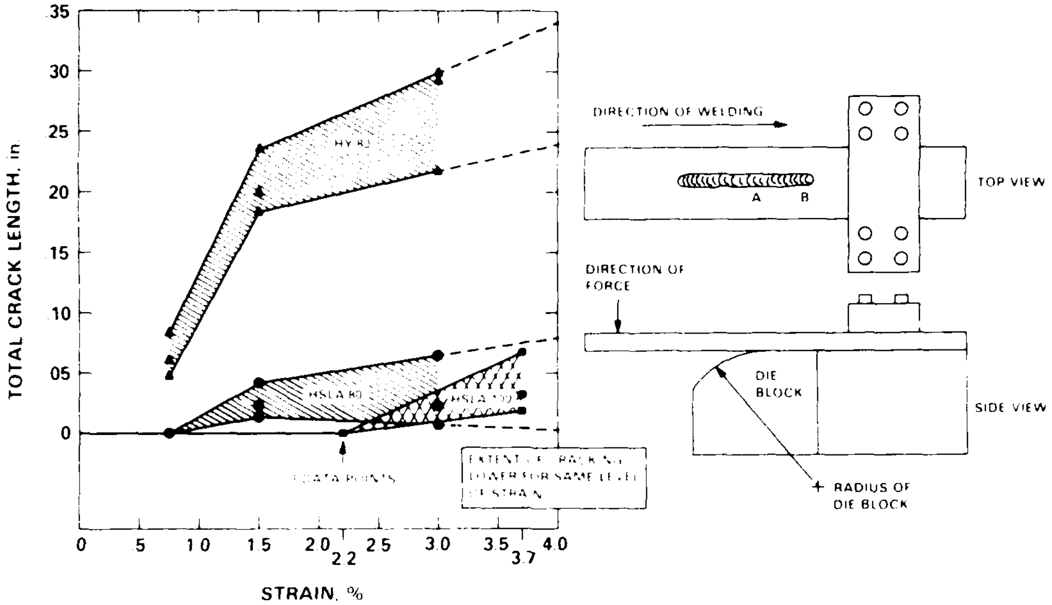


Fig. 7. Results of varestraint tests of high strength steels for hot cracking resistance.

		C	Mn	P	S	Si	Cr	Ni	Mo	Cu	Cb	V	B	C.E.*
TRADITIONAL NAVY STRUCTURAL STEELS	HY-80	.15	.25	.01	.01	.25	1.40	2.70	.40	.05	—	.01	—	0.78
	HY-100	.17	.25	.01	.01	.25	1.40	2.90	.40	.05	—	.01	—	0.81
CURRENT DEVELOPMENT HSLA (CONV. ALLOY)	HSLA-80	.04	.55	.01	.005	.30	0.70	0.90	.20	1.20	.04	—	—	0.50
	HSLA-100	.04	.90	.01	.005	.25	0.60	3.50	.60	1.60	.03	—	—	0.81

*C.E. = CARBON EQUIVALENT

CARBON EQUIVALENT

$$CE = C + \frac{Mn + Si}{6} + \frac{Ni + Cu}{15} + \frac{Cr + Mo + V}{5}$$

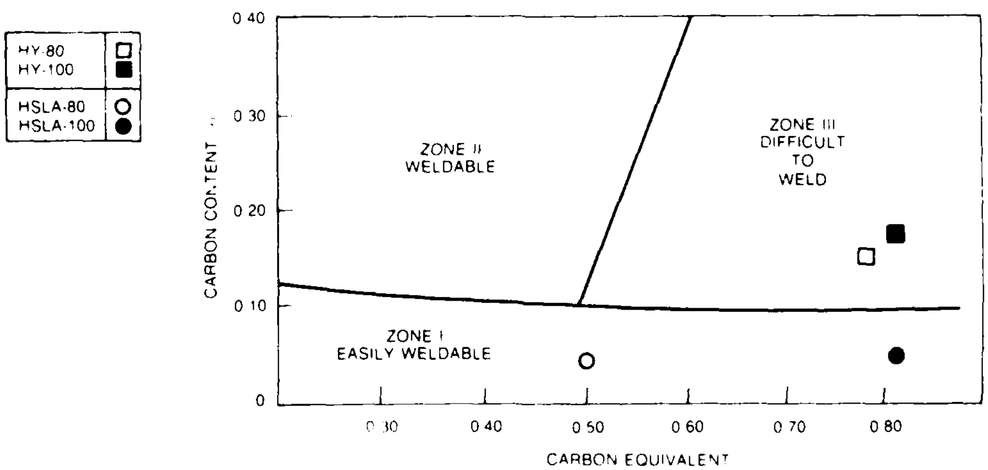


Fig. 8. Chemical compositions, carbon equivalents, and weldability diagram for high strength naval steels.

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